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REGULATION OF ELECTRIC POTENTIAL, CAUSED BY FRICTION OF PARTICLES OF MILK POWDER DRYING PROCESS

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ABSTRACT

The aim of the article is to investigate the phenomenon of Triboelectricity, as the physical process called in technical literature as "Tribocharge". Tribocharge process occurs during drying industrial lines operation and comprising different elements: e.g., cyclones, pneumatic lines, instantizers, storage hoppers, etc. In our scientific studies, the food product – powder milk is used as the basis. The experimental unit for investigation of these phenomenon elements in laboratory conditions is presented. The results of powder milk particle Tribocharged depending on the experimental tasks and conditions have been revealed. The presented scientific studies are referred to Tribocharge investigation, aimed at the development of the methods eliminating or reducing the negative results arising in the process of spray drying. Tribocharge actively influences the extent of particles cohesive and adhesive bonds and consequently the intensity of powder milk deposits on inner sides of drying equipment and other negative phenomenon during its operation.

KEYWORDS: Drying Unit, Statics, Electricity at Friction & Specific Electric Charge

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Original Article

INTRODUCTION

In practice, the states in which powder milk products obtained by spray drying method exist may be very different, e.g., static and dynamic, and they differ by the character of the particles packing, adhesion and cohesion interaction between them. The phenomenon itself under the term "Triboelectricity" has been known long ago in principle, from the time when the first information about electricity as such appeared. Thus, in turn, the physical processes connected with "Triboelectricity", namely particles. Tribocharge play very important role in the mentioned interactions.

Tribocharge is very complicated and volumetric process, which occurs during friction of different similar particles or particles contacting with heterogeneous materials as metals or materials relating to conductors [1, 2]. For example, the physical process of Tribocharge arises in the process of technological equipment operation ensuring spray drying, influencing the efficiency, and in some case explosion safety of process on the whole.[3]

HISTORY OF PROBLEMS

In the process of spraying and drying dry milk particles, suspension can accumulate on the inner surfaces of the drying equipment or by repeatedly contact between each other and the walls of the transporting ducts. During these

processes, static charge accumulation in the product (dry milk) occurs that requires grounding of drying unit circuit [4, 5] or improving drying chamber walls and air ducts surface characteristics [6].

The data relating to investigation of dry milk particles' electric potential are comparatively not numerous and require further systematization. Japanese scientist Shin'ichi Taneya from Japan Research Laboratory, Snow Brand Milk Products Ltd., published his investigations in Japan Journal of Applied Physics[7]. In his works, in which he recorded in detail, in graphics and textural descriptions, stated that electrization of sprayed drops of condensed skim milk and other products, which are produced in the process of spray drying, can be studied on the basis of electric potential investigation inside the flow of these sprayed drops.

Shin'ichi Taneya concluded that the largest part of sprayed drops dried in particles, less than 100 (µ) micron in radius, are positively charged while bigger drops are negatively charged. By this similar method, this scientist studied electrization of dry skim milk particles in pneumatic line. Then he (Taneya) found out that the higher the particles' concentration in ratio with their accelerated velocity in the flow, the higher the total charge of these particles, i.e., the charge potential increases. Herewith, dry particles are charged positively.

He determined the total charge of the powder-electrified particles in the process of drying by means of V-shaped tray (chute) after which the particles in the stage of free fall get (d) AC field which caused sinusoidal tracks (oscillations) of these particles.

Moreover, the author determined that dry particles of such products as dry skim milk, dry butter, flour and dry lactose and others of "small" dimensional classes approximately less than 10 (µ) microns in radius are mainly charged positively.

With all these, some number of particles, which are charged positively "lose" this charge (i.e. become neutral) when these particle sizes is changed. The particles, which are bigger or equal to 40 (µ) micron in radius, are electrically neutral.

In the other scientific work, the authors say that during friction with each other or with inner surface of the equipment, for example, in pneumatic or aerosol transport, the product particles obtain electric charges stipulating the appearance of adhesion electric forces.

Electric forces of adhesion inherent to dry milk products particles influence the drying unit operation, pneumatic transport systems, explosion safety, efficiency of the particles' agglomeration process and milk powder reconstitution.[8,9] These forces occur only under the particles' contact with the technological equipment surface. Electric forces of adhesion depend on dry product particles' size, composition and the equipment surface material they contact. The smaller particles' size is the bigger charge dry milk possess.[10]

When the Coulomb forces of the particles on the surface rise, they are fastly reduced when they come into contact with the surface of the particles. The residual Coulomb forces depend on moisture particles and electrical conductivity of surface equipment. Depending on the number of particles sticking to solid surface, they can locate on it without touching each other or form the layer of contacting particles.

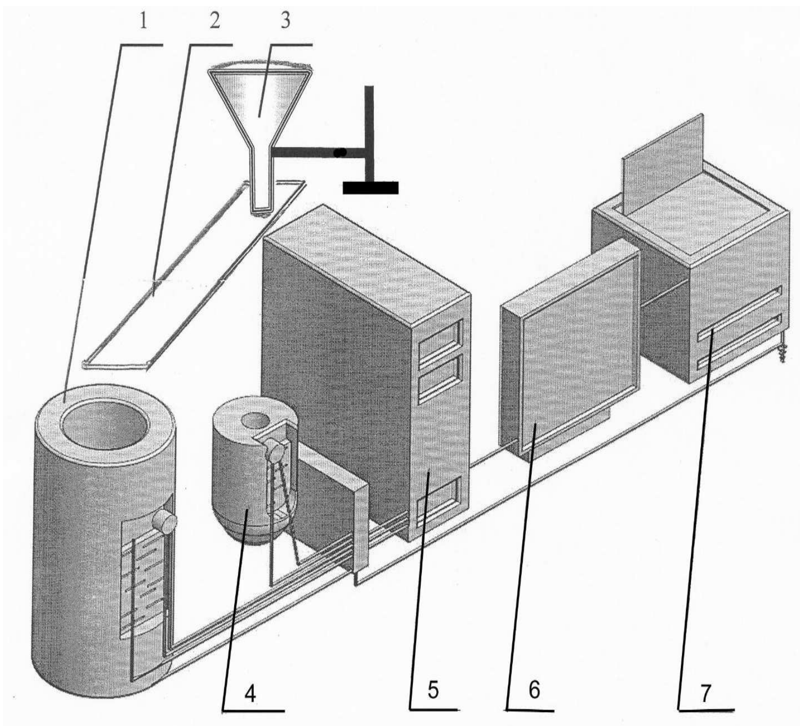
Simon[11] makes the conclusion that such layer strength depends not only on its adhesion to the surface but the number of interacting particles and interacting forces between them. At present, a lot of works covering powder materials'

adhesion is well known[12].

It should be considered that adhesion interaction of particles and only electric forces of adhesion do not limit the surface. On the whole, particle adhesion to the solid surface is affected mainly due to molecular forces, capillary forces of the liquid condensing in the gap between contacting bodies as well as under the action of double electric layer forming in the contact zone and Coulomb interaction. Under the specified conditions, the strength of one kind can prevail under the others. So, for example, at air relative moisture higher than 70% or moisture content in milk powder higher than 7%, capillary forces start to render dominating sense on enhancement of adhesion[13]. As for the electric potential of the particles, the scientist Tanaka Tatsuo from Japan determined that moisture reduces the explosive risk situation, decreasing the period of the charge breakup (if the powder is hydrophobic)[14].

METHODOLOGY OF THE STUDIED WORK

In our studies, powder skim milk is used as the basic food product. The investigation covering Triboelectricity of skim milk powder particles is necessary for studying production processes connecting with drying of different materials including drying of whole milk. Faraday cylinder method was used for determination of electric charge of powder milk particles mass[15]. The stand presented at Figure 1 was constructed for Triboelectricity measurement. "Tribocharge" was determined on the inclined base plate made from stainless metal X18H10T grade and dielectric (polyethylene terephthalate). In the subsequent processes, the inclined base plate on stainless metallic base X18H10T and dielectric (polyethylene terephthalate) were used for the investigation and the length "H" of these inclined base plates was varied in the range from 50 to 300 mm.



1. Faraday Cylinder; 2. Inclined Base Plate; 3. Feed Hopper Receiver; 4. Adapter; 5. Processor on IBM base with Integrated Electrostatic Voltmeter and Electrometer; 6. Monitor; 7. Printer.

Figure 1: The Experimental Stand for Measuring of Triboelectricity of Skim Milk Powder Particles.

The purity of the treatment of metallic stainless steel base plate on standard deviation of the surface roughness on the level of N_{sk} = 0,2 (μ) micron.

Measurements were executed as follows: dry skim milk particles were poured into feed hopper (receiver) 3. After receiver, 3 skim milk powder particles by smooth flow during the process of free fall from the height H = 150 mm got on the ramp of the bottom layer 2.

Angle of slope of inclined base plate 2 to horizontal plane made up 45^o. The portion of skim milk powder due to adhesive strengths specified by Coulomb forces (electric forces) were fixed on the inclined base plate surface.

Herewith, the metal base plate was grounded. The other – the basic part of the particles in the form of skim milk powder got into the special vessel 1 under the term “Faraday cylinder”.

After each experiment, the portion of skim milk powder, which got directly into Faraday cylinder was weighed.

Faraday cylinder is screened device completely protected against applied electric field impact. The capacity of measuring circuit “C” comprises the capacity of the instrument, receiver of particle and wires, C = 1,72 – 10^{-10} F – const.

The acquired potential and polarity of skim milk powder particles that got into Faraday cylinder were determined in the form of defined signal frequency. This signal is simulated via adapter 4 and analyzed by processor 5 on IBM base.

This processor 5 represents the device that besides the basic functions of the ordinary computer executes the tasks covering the determination of the potential and polarity of skim milk powder particles that occurred in Faraday cylinder. Notably, by means of defined electronic board, electrostatic voltmeter and electrometer are integrated into the processor 5.

The readings are analyzed on the monitor (display) 6 of the said instrument and if necessary are transferred to the paper by means of printer 7. Skim milk powder particles mass that occurred in the receiver was measured on electron weight with the accuracy (+/–) 0, 01 gm.

Skim milk powder particle potential was determined at T = 20°C and air relative humidity 75–80%.

The particles’ traverse speed from receiver 2 to Faraday cylinder capacity was changed in the range from 0, 1 to 2 m/sec depending on the change of specific electric charge of skim milk powder particles.

The specific electric charge of the particles (Coulomb/kg) pouring in the receiver was determined by the formula:

$$\boldsymbol{q_{sp} = CU/m} \tag{1}$$

where, C – capacity of the measuring circuit, Farad;

U – voltage registered on the monitor, Volt;

m – mass of skim milk powder particles, kg.

The experimental results were registered in Table 1.

THE RESULTS OF THE RESEARCH

Table 1: The Parameters of Skim Milk Powder Specific Electric Charges under Tribocharge

Variable Parameter	Dependence of Specific Electric Charge from Length of Inclined Base Plate						
L length of inclined base plate	0	50	100	150	200	250	300
q_{sp}, x10^{-8} Coulomb/kg U=150 Volts dielectric polyethylene terephthalate	45	24	6,0	1,6	1,0	0,8	0,8
q_{sp}, x10^{-8} Coulomb/kg when U = 100 Volts dielectric polyethylene terephthalate	27	18	6,0	2,3	1,8	1,6	1,6
q_{sp}, x10^{-8} Coulomb/kg when U=0 Volt dielectric polyethylene terephthalate	18	12	6,0	3,4	2,9	2,8	2,8
q_{sp}, x10^{-8} Coulomb/kg U=100 Volts stainless metal X18H10T.	0	4,5	6,0	9,0	15,0	25,0	40,0

It became clear that with the increase, the length of the path traveled by particles of powder milk significantly increased the specific area of contact between the particles with the contacting surface of the metal inclined base plate 2, which contributed to the ascending values of specific electric charges.

Herewith, it was stated that all the particles of dry milk acquire the positive polarity charges as far as the formed ones on the free electrons are easily transferred to metal inclined base plate, i.e., conductor, which was grounded. Under replacement of metal inclined base plate for dielectric (polyethylene terephthalate) in the process of Triboelectrization, the charges of opposite polarity were accumulated on the inclined base plate as well as on skim milk powder particles.

Herewith, the potential differences between the inclined base plate surface and particles was increased and was registered on monitor 6 and it promoted the particles gravitation to inclined base plate. Due to the great importance of skim milk powder particles' contact area (ingenuous accumulation of particles on the backing) Tribocharge process and the following discharge process occur more intensively ("heaping" of particles into Faraday cylinder). On application of metal inclined base plate, the increase of specific charges of skim milk powder particles depending on velocity occurs insignificantly. The investigation results relating to evaluation of specific electric charges of skim milk powder under different conditions of its movement down the inclined base plate are graphically shown in figure 2.

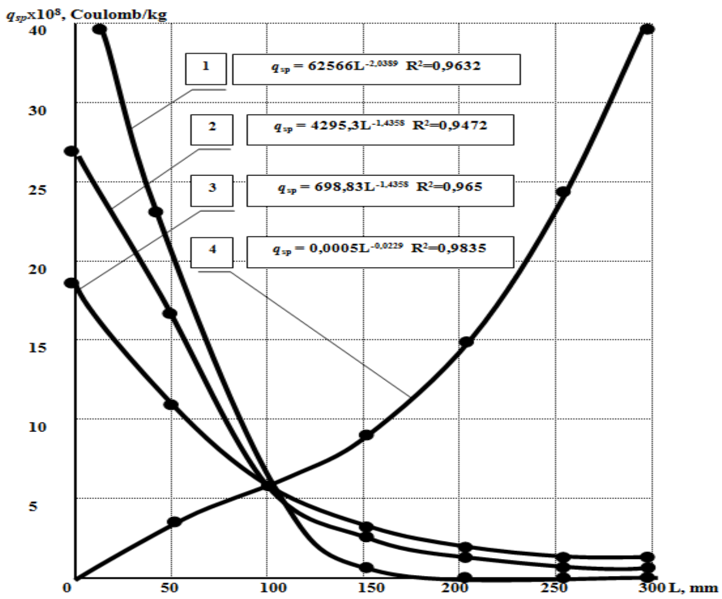


Figure 2: Dependence of Specific Electric Charges under Tribocharge on the Range of the Length of Metal and dielectric Inclined Base Plate.

1. Dielectric inclined base plate U = 150 V. **2. Dielectric inclined base plate U = 100 V.**

3. Dielectric inclined base plate U = 0 V. **4. Metal inclined base plate U = 100 V.**

In the voltage from 0 to 150 volts, the specific electric charge decreases with increasing voltage, subject to the dependence according to the above formulas.

However, when the inclined base plate is used, the specific electrical charges of particles are fast depending on the velocity of these particles (figure 3).

These values correspond to the exponential dependence and obey the equitation (formula) 2.

$$q_{sp} = ae^{-bL} \tag{2}$$

where, $\mathbf{a} = 5{,}0013$; $\mathbf{b} = -6{,}9\text{x}10^{-3}$

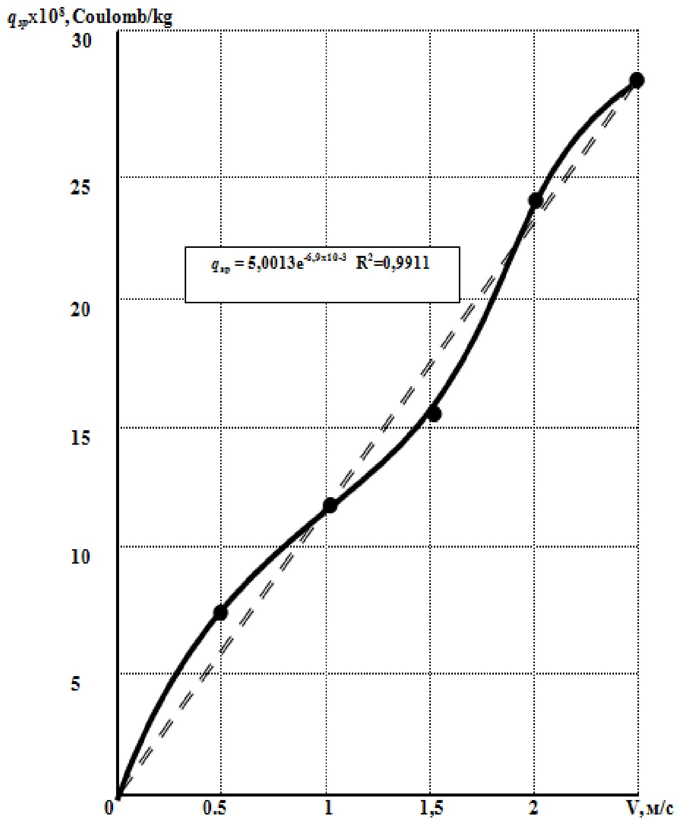


Figure 3: Change of Specific Electric Charge of Powder Milk Particles under Tribocharge Depending on the Particle Movement Velocity under the Length of Inclined Base Plate L = 300 Mm.

With an increase in voltage (growth Tribocharge) the specific electric charge increases according to the formula $\mathbf{q_{sp} = 5{,}0013e^{-6,9x10-3}}$, $\mathbf{R^2 = 0{,}9911}$.

Moreover, it has been established that an increase in the specific electrical charges by the particles of dry skim milk is facilitated by a reduction in the electrical potential applied to the metal inclined base plate. Processing of experimental date on the process of Triboelectricity of particle of dry skim milk makes it possible to obtain the mathematical model of this phenomenon.

ANALYSIS OF THE EXPERIMENT RESULTS

Using a mathematical model to calculate internal and external transfer of electrical charge for a single particle as well as the tension of the electrical field and its change in the space inside and outside the investigated particle dry skim milk.

For the calculations, use the value of specific electric charge 6.0 x 10^{-8} Coulomb/kg (Table 1), which is the same as the point of intersection of the graphic curves and hypothetically is the average of the experimental results.

Using the experimental data in the study of Triboelectrical particles of dry skim milk can be presented as a mathematical model of Tribocharging particles and also to provide internal and external transfer of electrical charge for a single particle. In addition, calculate the potential tension electric field and its change in the space inside and outside of the skimmed milk powder particles.

The effect of Triboelectrization is the result of exchange between the particles contacting areas and according to some scientists' opinion described in their manuscripts[16, 17] is connected with formation of general in the contact area double electric layer which acts as ingenuous source of static electric charges.

Energy state of the areas prior their contact is characterized by the specific equilibrium state. Under the areas contact, their energy state is upset as the areas having different level of surface energy come into effect[18, 19]. Newly formed double electric layer equal to several micrometers is characterized by new electric state.

Under loss of contact, non-compensated electric charges of opposite sign are formed on each particle of the dried product, the size of which is defined by kinetics of processes occurred under formation and break of double electric layer in the place of these particles' contact.

For each case study, kinetics of electric charges communication depends on several factors connected with electric characteristics of contact phase and specific conditions under which Triboelectrization process occurs[20].

The presented mathematical model should be considered as the first stage in solving the very complicated tasks of Triboelectrical phenomenon underlined in the process of condensed skim milk drying.

MATHEMATICAL MODEL OF TRIBO CHARGING PARTICLES

The Numerical Values of the Potential Voltage Electric Field

The inner and outer electric charge transfer of Powder milk powder separate particle depends on electric field and the potential inside and outside of the particle which can be conditionally taken for sphere in radius $R = A$ and charged current with volume density p_v, C/m^3, (Figure 4) [21].

Let us consider the voltage of field inside the sphere $(R < A)$, on spherical particle surface $(R = A)$ and out of it $(R > A)$ according to Gauss theorem[22].

Quantity of electrical charge in a spherical particle:

$$q = V p_v = (4/3)\, \pi A^3 p_v. \quad (3)$$

Electric field, created out of spherical particle coincides with the field created by equivalent to point charge. According to Coulomb law, the voltage of such field $(R > A)$ make up:

$$E_{EX} = k\, q / R^2 = q / (4\, \pi\, \varepsilon_0\, R^2) = A^3 p_v / (3\, \varepsilon_0\, R^2) \quad (4)$$

The voltage of electric field on the surface ***(R = A)*** of spherical particle make up:

$$E_{SF} = A^3 p_v/(3\,\varepsilon_0\,A^2) = A\,p_v/(3\,\varepsilon_0) \tag{5}$$

The voltage of electric field inside spherical particle **(R < A)** is changed linearly from zero in the center to peak value on the surface:

$$E_{IN} = R\,p_v/(3\,\varepsilon_0) \tag{6}$$

$\varepsilon_0 = 8{,}85\ 10^{-12}\ C^2/(H\ m^2)$ - electric constant.

Difference of potentials in the inside field of spherical particle between spherical of radiuses R_1 and R_2 make up:

$$U_{R1} - U_{R2} = \int_{R2}^{R1} E_{IN}\,dR = (R^2{}_1 - R^2{}_2)\,p_v/(6\,\varepsilon_0) \tag{7}$$

So, in particular, the difference of potentials between center of the particle and its surface make up:

$$U_A - U_0 = A^2 p_v/(6\,\varepsilon_0) \tag{8}$$

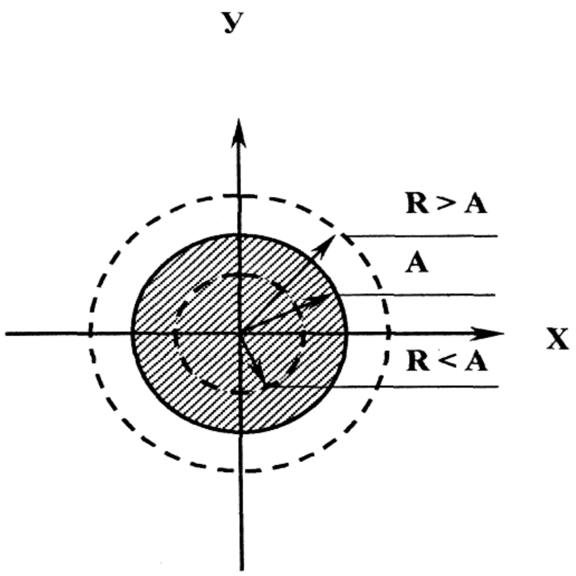


Figure 4: Spherical Particle of Powder Milk Powder in Radius R = A.

The difference of potentials in external field particle between spherical shells of radiuses R_1 and R_2 make up:

$$U_{R1} - U_{R2} = \int_{R2}^{R1} E_{EX}\,dR = (1/R_2 - 1/R_1)\,A^3 p_v/(3\,\varepsilon_0) \tag{9}$$

So, in particular, the difference of potentials between spherical particle surface and infinity make up:

$$U_A - U_\infty = A^2 p_v/(3\,\varepsilon_0) \tag{10}$$

If we take the potential at infinity, remote point equals zero:

$U_\infty = 0$

Then, potentials on surface U_A and in center U_0 of spherical particle are:

$$U_A = A^2 p_v/(3\ \varepsilon_0) \quad (11)$$

$$U_0 = A^2 p_v/(6\ \varepsilon_0) \quad (12)$$

According to the above-mentioned formulas, we can calculate electric field and potential inside and outside particles of Powder milk particle d = 60 μ charged by electric current with specific density per mass unit. Take the value (data) of Table 1.

$$\rho_m = 6 \cdot 10^{-8}\ C/kg$$

Since Powder milk bulk density makes up **560–580 kg/m³**, so specific volume will make up **1,7·10⁻³ m³/kg**; so specific density of electric charge per volume unit will make up:

$$\rho_v = 3{,}53 \cdot 10^{-5}\ C/m^3$$

Then the voltage of electric field on the surface of particle Powder milk will make up:

$$E_{SF} = A\ p_v/(3\ \varepsilon_0) = 3{,}0 \cdot 10^{-5}\ m\ 3{,}53 \cdot 10^{-5}\ C/m^3\ / \ /\ (3\ 8{,}85 \cdot 10^{-12}\ C^2/(H\ m^2)) = 0{,}4 \cdot 10^2 H/C = 40\ V/m \quad (13)$$

The voltage of electric field on the external of the spherical particle Powder milk E_{EX} at $R = 1\ 10^{-4} m$ will make up:

$$E_{EX} = A^3 p_v/(3\ \varepsilon_0\ R^2) = (3{,}0 \cdot 10^{-5}\ m)^3 \cdot 3{,}53 \cdot 10^{-5}\ C/m^3/ \ /(3 \cdot 8{,}85 \cdot 10^{-12}\ C^2/(Hm^2) \cdot (1{,}0 \cdot 10^{-4}\ m)^2) = 3{,}6\ H/C = 3{,}6\ V/m \quad (14)$$

For $R = 1 \cdot 10^{-3} m$, E_{EX} make up:

$$E_{EX} = A^3 p_v/(3\ \varepsilon_0\ R^2) = (3{,}0 \cdot 10^{-5}\ m)^3 \cdot 3{,}53 \cdot 10^{-5}\ C/m^3\ / \ /(3\ 8{,}85 \cdot 10^{-12}\ C^2/(Hm^2)\ (1{,}0 \cdot 10^{-3} m)^2) = 3{,}6 \cdot 10^{-2} H/C = 0{,}036\ V/m \quad (15)$$

$E_{EX} = 3{,}6 \cdot 10^{-4}\ V/m$ for $R = 1 \cdot 10^{-2}\ m$, E_{EX} make up:

$$E_{EX} = A^3 p_v/(3\varepsilon_0 R^2) = (3{,}0 \cdot 10^{-5}\ m)^3\ 3{,}53 \cdot 10^{-5} C/m^3/ \ /(3 \cdot 8{,}85\ 10^{-12} C^2/(Hm^2)\ (1{,}0 \cdot 10^{-2} m)^2) = 3{,}6 \cdot 10^{-4} H/C = 0{,}00036\ V/m \quad (16)$$

$$E_{EX} = 3{,}6 \cdot 10^{-6} V/m$$

Quantity of electricity in a spherical particle Powder milk:

$$q = (4/3)\pi A^3 p_v = 4/3 \cdot 3{,}14\ (3{,}0 \cdot 10^{-5} m)^3\ 3{,}53 \cdot 10^{-5} C/m^3 = 4 \cdot 10^{-18} C \quad (17)$$

Difference of potentials relative to infinity for the center of the spherical particles make up:

$$U_0 = A^2 p_v/\ (6\varepsilon_0) = (3{,}0 \cdot 10^{-5} m)^2\ 3{,}53 \cdot 10^{-5} C/m^3\ (6 \cdot 8{,}85 \cdot 10^{-12} C^2/(Hm^2) = 0{,}6 \cdot 10^{-3} Hm/C = 0{,}0006\ V \quad (18)$$

$$U_0 = 6 \cdot 10^{-5}\ V$$

Difference of potentials relative to infinity for the surface of the spherical particle make up:

$$U_A = A^2 p_v/(3\varepsilon_0) = (3{,}0 \cdot 10^{-5} m)^2\ 3{,}53 \cdot 10^{-5} C/m^3//(3 \cdot 8{,}85 \cdot 10^{-12} C^2/(Hm^2) = 1{,}2 \cdot 10^{-3} H\text{м}/C = 0{,}0012\ V \quad (19)$$

$$U_A = 12 \cdot 10^{-5}\ V$$

The diagrams of the voltage electric field ***E*** and difference of potentials ***U*** with infinity point as function R distance from the center of remote spherical Skim milk particle are presented at Figure 5.

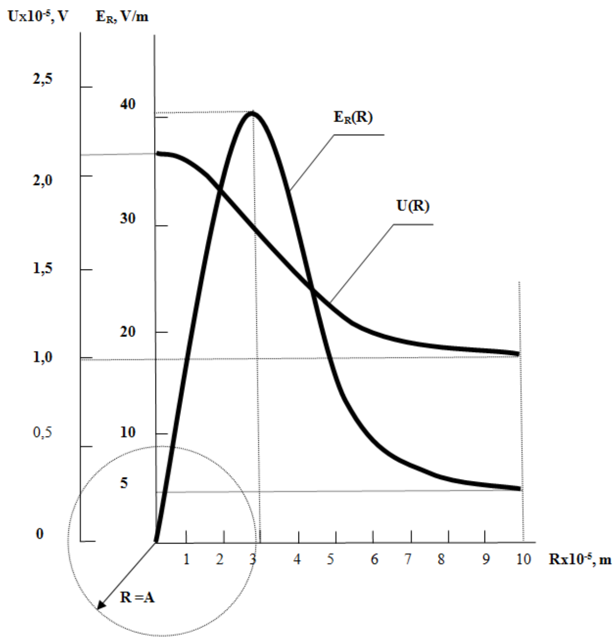


Figure 5: Distribution of Voltage E (R) and Difference Potentials U (R) Electric Field Inside and Outside of the Single Spherical Particles of Powder Milk.

CONCLUSIONS

During transportation, dry milk particles obtain electric charge as a result of friction with inner surfaces of the technological equipment. Static electricity elimination is quite a multi-aspect task requiring complex technical solutions aimed at creation of safe system of transportation and storage of dry milk produced by spray-drying process. In our scientific experiments, the attempt was taken to study and investigate Triboelectrical phenomenon not only in laboratory conditions but also on the industrial scale in the process of milk drying[23, 24].

The present work represents the additional experimental materials characterizing the peculiarities of dry skim milk particles Tribocharge. The mathematical model of inside and outside transfer of electric charge for a separate skim milk particle is presented. The algorithm of inside and outside of electric charge transfer determination in a separate dry skim milk particle which depends on electric field and the potential inside and outside of the particle is proposed. The numerical values of electric field strength outside and on the particle surface as well as voltage (potential) in the center, inside and on the surface of dry skim milk particle have been determined.

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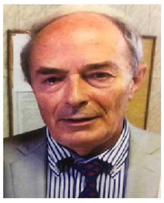

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